History and Results From The Two Decade Quest To Measure The Earth's Radiation Budget

by

Thomas H. Vonder Haar
(Thomas.Vonderhaar@colostate.edu)

Department of Atmospheric Science

College of Engineering

Colorado State University

ERB Workshop

NCAR, CGD, Boulder CO

September 13, 2018

Abstract

The first global measurements of Earth's emitted thermal energy and the amount of solar energy it absorbs from the Sun were made from early satellites in the **1960's to 1980's**. They provided a much different Radiation Budget than had been thought in the pre-satellite era. Following the scientific method, two additional satellite missions were used to confirm the first measurements by Vonder Haar and Suomi (1969, 1971). The early instruments and satellites are discussed. The new scientific results and their implications for Earth's weather and climate systems are reviewed. Some lessons learned and suggestions for today's continuing research are provided.

Colorado State University
CIRA

Acknowledgements

- Thanks to my numerous students, colleagues and co-authors who joined in this research on observations of Earth's Radiation Budget
- During more than 2 Decades covered in this review, special thanks to the Science and Engineering members of:
  a) the DMSP SS/RB Flat Plate Radiometer Team
  b) the Nimbus-3 and Nimbus-7 ERB Earth Radiation Budget Teams
  c) The ERBE (Earth Radiation Budget Experiment) teams for the Shuttle launch and for NOAA-9 and NOAA-10
- In recent years John Forsythe, John Haynes and Curtis Seaman have helped with this Review

Box 1 | Updated energy balance

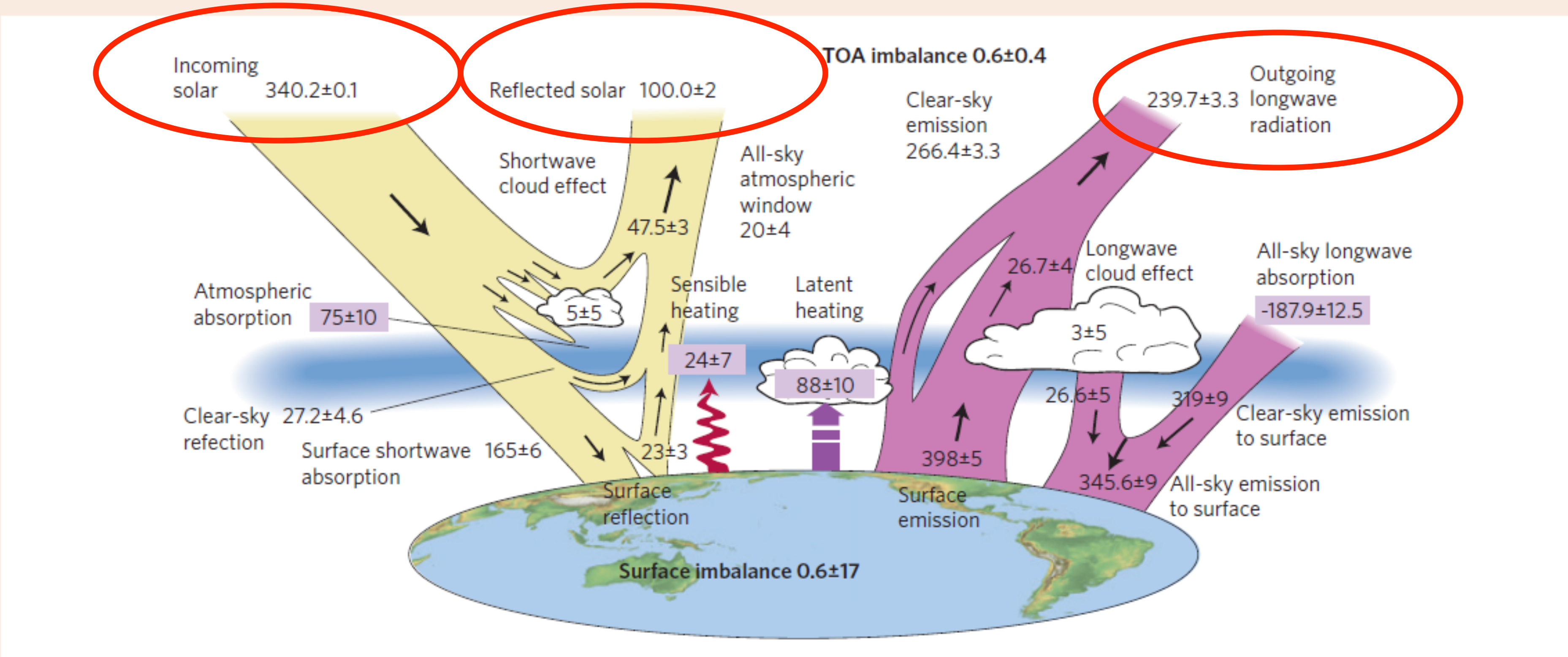
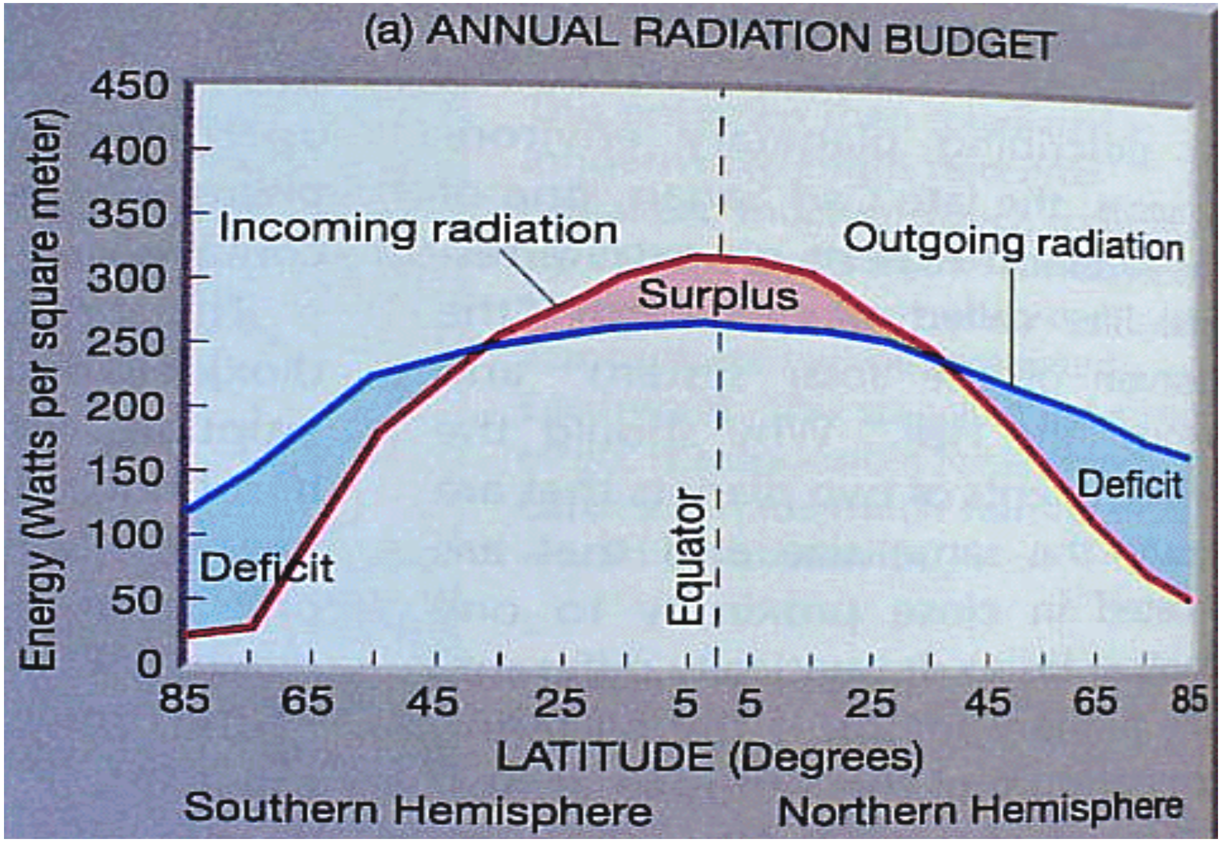


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.

Stephens, G.L., J. Li, M. Wild, C.A. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P.W. Stackhouse, M. Lebsock, T. Andrews, An update on the Earth's energy balance in light of new surface energy flux estimates, Nature Geosci, 5, 691-696, doi: 10.1038/ngeo1580.

Radiation Budget at the top of the Earth's Atmosphere



The Amount and Space/Time Distribution of Earth Radiation Budget "Surplus" and "Deficit" at the Top-of-the-Atmosphere is the FUNDAMENTAL DRIVER of Earth's Weather and Climate … and Earth's Biosphere.

Earth Radiation Budget Estimates in the Pre-satellite Era

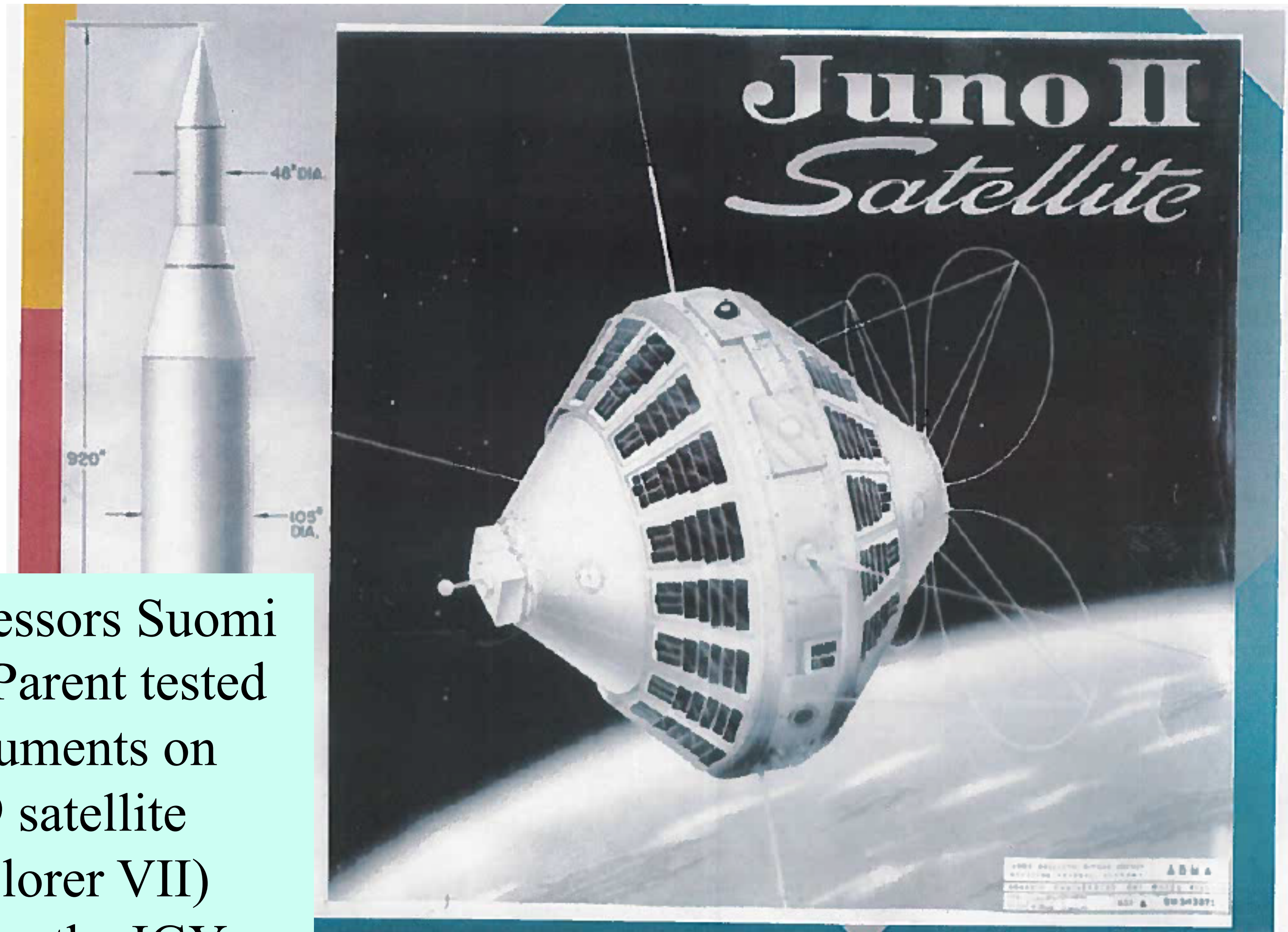
Author	Planetary Albedo
Dines (1917)	50%
Simpson (1928)	43%
Lettau (1954)	34%
London (1957)	32 %

Satellite Measurements

Vonder Haar & Suomi (1969,1971) 29% ± 1%

Colorado State University CIRA

Good artist's depiction of black and white radiometers on the equator of an early satellite – but the launch rocket exploded!



Professors Suomi and Parent tested instruments on 1959 satellite (Explorer VII) during the IGY

TIROS with the Suomi ERB sensors

Defense Satellite Application Program satellite

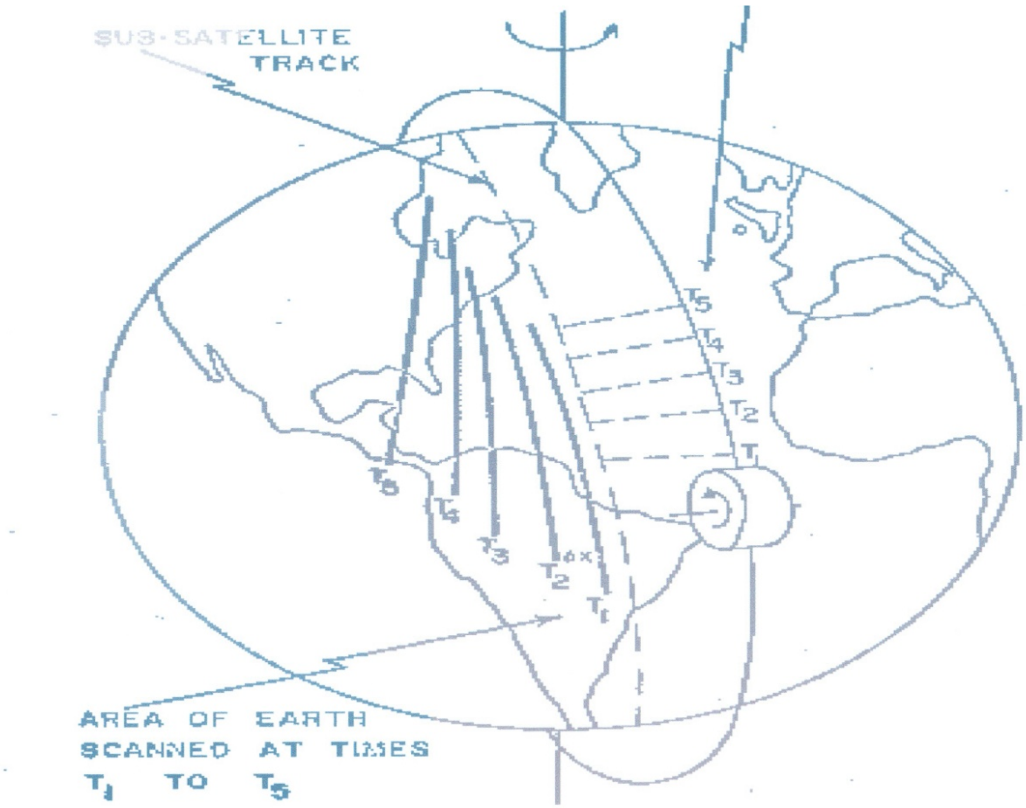
These USAF DMSP Block 1 satellites were launched in the mid-1960's and carried Earth radiation budget radiometers.

Diameter: 58 cm
Height: 53 cm
Mass: 45 kg
4 FPR sensors = 0.7 kg

Inclination: ~98°
Height: ~833 km

Colorado State University CIRA

During the 1960's we used TIROS (i=47° or 57°) and experimental USAF (1st sun-sync orbits (~98°)) to, literally, piece together an understanding of ERB. The research of Vonder Haar and Suomi (V&S Science, 1969; JAS, 1971) gave us the early low resolution view of the Global Earth's Radiation Budget.



Early USAF pre-DMSP satellites carried ERB sensors in near polar orbits

Black Flat Plate Radiometer for Earth Radiation Budget flown on pre-DMSP satellites in the mid-1960's (Suomi, Parent, Vonder Haar et al.)

Colorado State University
CIRA

Flat Plate Radiometers were Calibrated by the Direct Solar Energy at Each Terminator Crossing

At A:

T_S = f (Direct Solar Energy + Reflected Solar + Infrared)

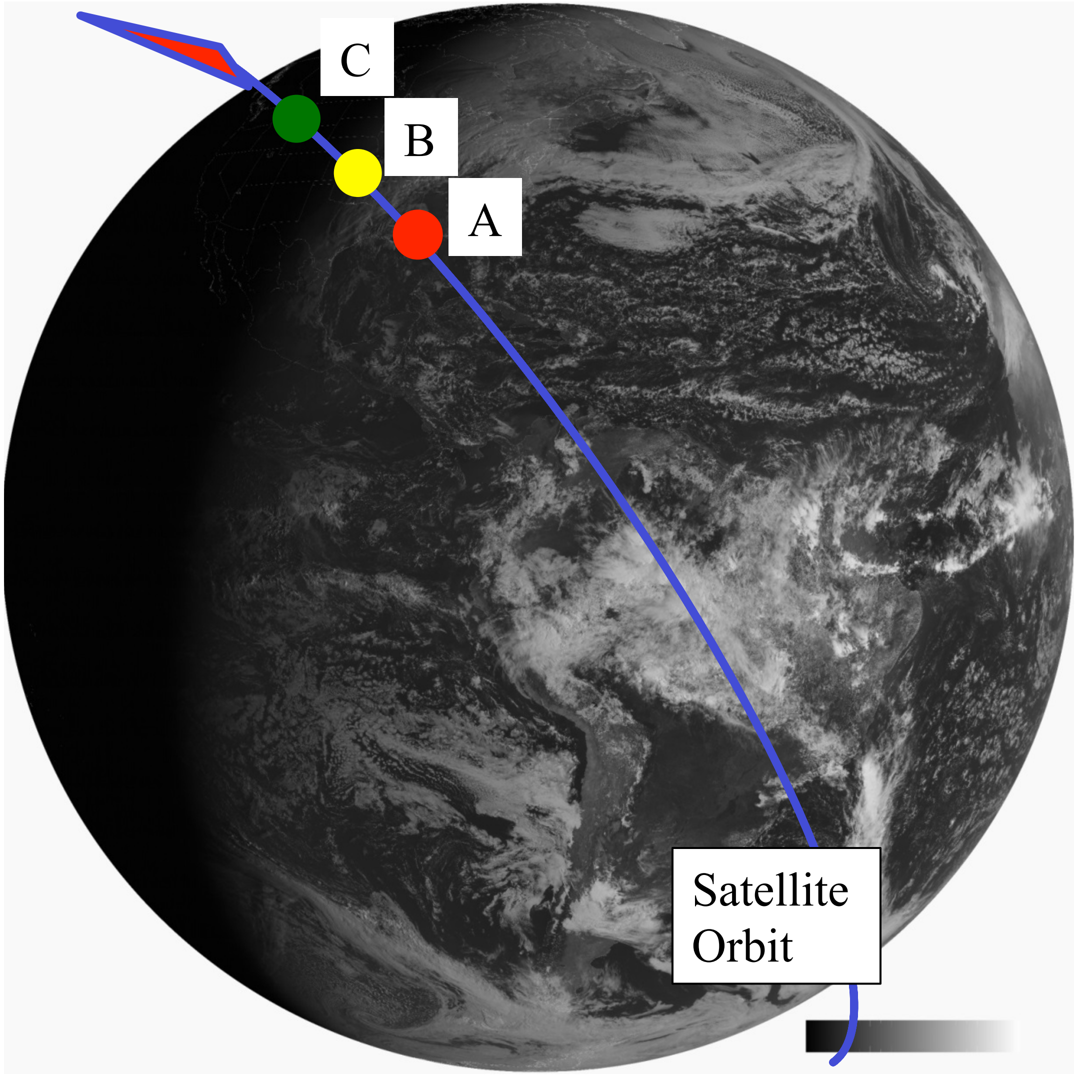
At B:

T_S = f (Direct Solar Energy + Infrared)

At C:

T_S = f (Infrared from Earth)

T_S = Temperature of Sensor of Flat Plate Radiometer



GOES-16 Visible 13:15 UTC 23 February 2018

Colorado State University CIRA

"We found that Earth was a Warmer and Darker Planet than previously believed - - especially in the Tropical Regions. We found that 40% More Energy must be transported poleward by the Atmosphere and Ocean Circulations!"

(Vonder Haar and Suomi, 1969, 1971)

Much more energy gain in the tropics

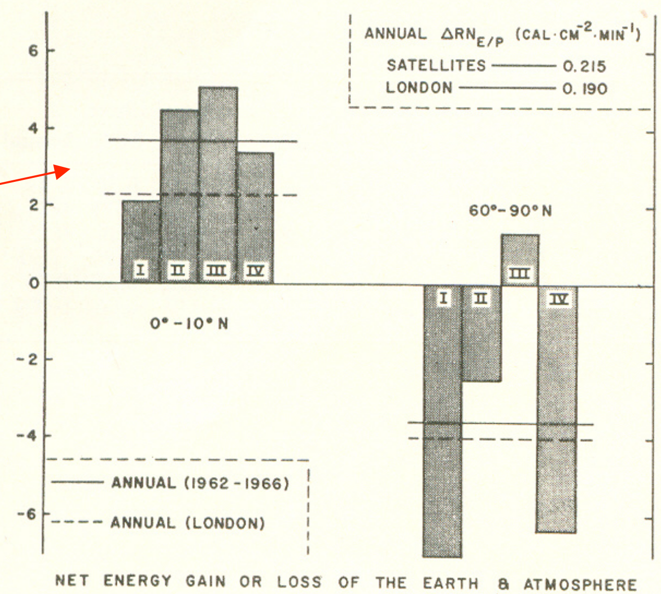
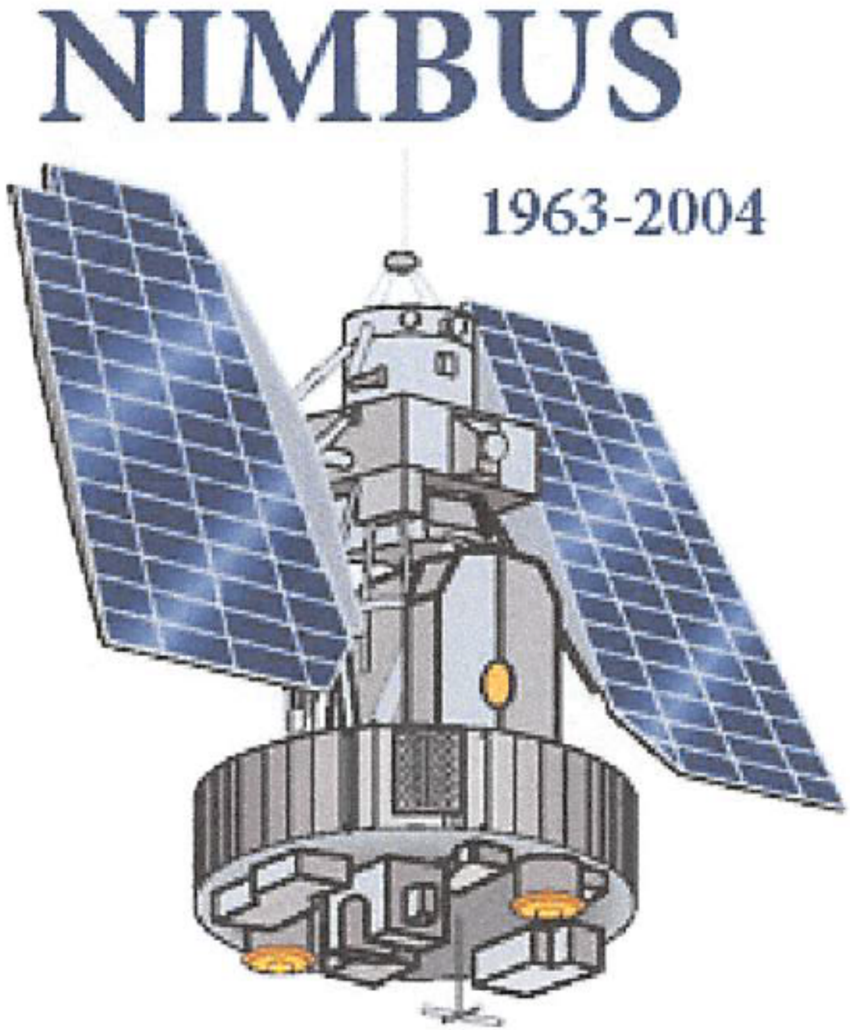


FIG. 2. Mean annual and seasonal energy exchange with space, measured from satellites during 1962–66, for two latitude zones. Bar graph represents seasonal values (I = Dec., Jan., Feb.; II = Mar., Apr., May; etc.). $\Delta RN_{E/P}$ is the net radiation gradient between equator and pole.

Could these early results be true?

If so, there were far-reaching implications to better understand and model Atmospheric and Ocean Circulations; Air-Sea Interactions; and both the Earth's Energy and Water Cycles!

The Nimbus 3 MRIR experiments, the Nimbus 6 & 7 ERB and the ERBE mission were designed to check, verify, and expand the results from the 1960's.



Colorado State University
CIRA

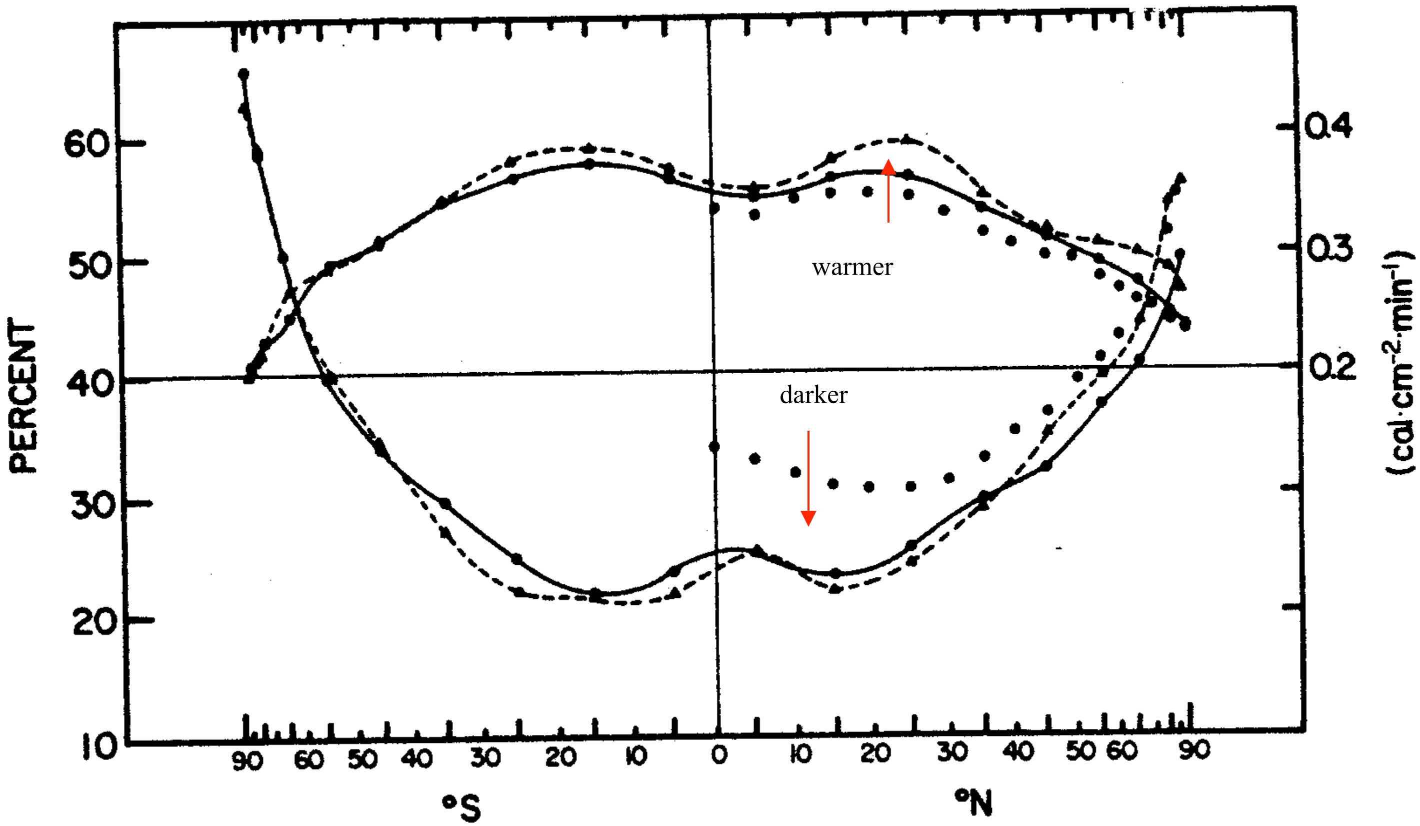
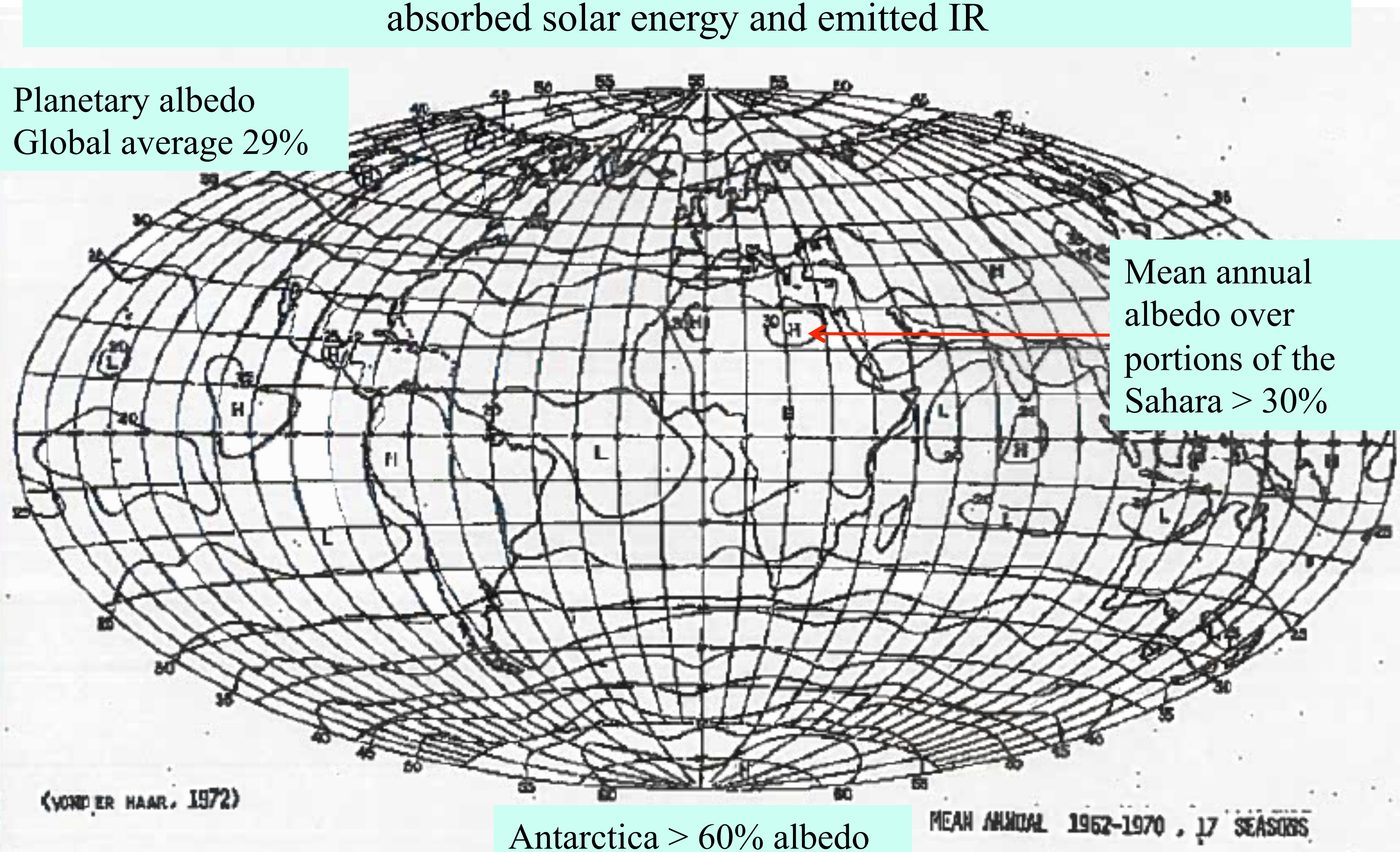


Figure 10.—Annual zonal averages of albedo (percent) and outgoing longwave radiation obtained from Nimbus 3 (dashed line) and earlier satellite (solid line: Vonder Haar and Suomi, 1971) and from calculations with climatological data (open circles: London, 1957).

So, Nimbus – 3 supports earlier satellite results!

Radiation budget climatology maps allow study of regional and seasonal absorbed solar energy and emitted IR

Planetary albedo
Global average 29%



Mean annual albedo over portions of the Sahara > 30%

Antarctica > 60% albedo

38   2 The Global Energy Balance

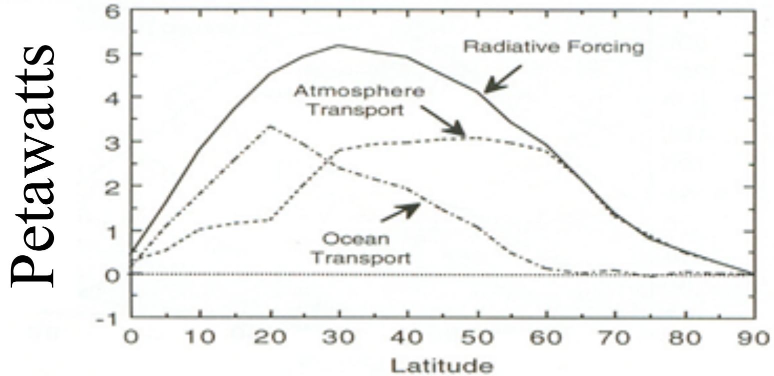


Fig. 2.14 Meridional transport of energy for annual-mean conditions. Net radiation and atmospheric transport are estimated from observations; ocean transport is calculated as a residual in the energy balance. [Adapted from Vonder Haar and Oort (1973). Used with permission from the American Meteorological Society.]

We can then use the observation of net radiation in Fig. 2.12 to derive the required annual-mean energy transport in the north–south direction. If we integrate the net radiation over a polar cap area, we can calculate the total energy flux across each latitude belt in the following way:[3]

$$\int_{-\frac{\pi}{2}}^{\phi} \int_{0}^{2\pi} R_{\mathrm{TOA}} a^2 \cos\phi \, d\lambda \, d\phi = F_\phi \qquad (2.21)$$

“In 1976, there were some… studies published… the authors Vonder Haar and Oort found that (satellite and atmospheric) observations could only be reconciled if the ocean transported half the heat. Oceanographers seized upon this happy conjecture to show how relevant their field was to problems of world climate.”

(from The Collected Works of Henry M. Stommel, Vol. I, AMS Historical Monograph, 1995)

[3] Vonder Haar and Oort (1973); Oort and Vonder Haar (1976).

Global Physical Climatology, D.L. Hartmann, 1994, Academic Press

LESSONS LEARNED (1 of 2)

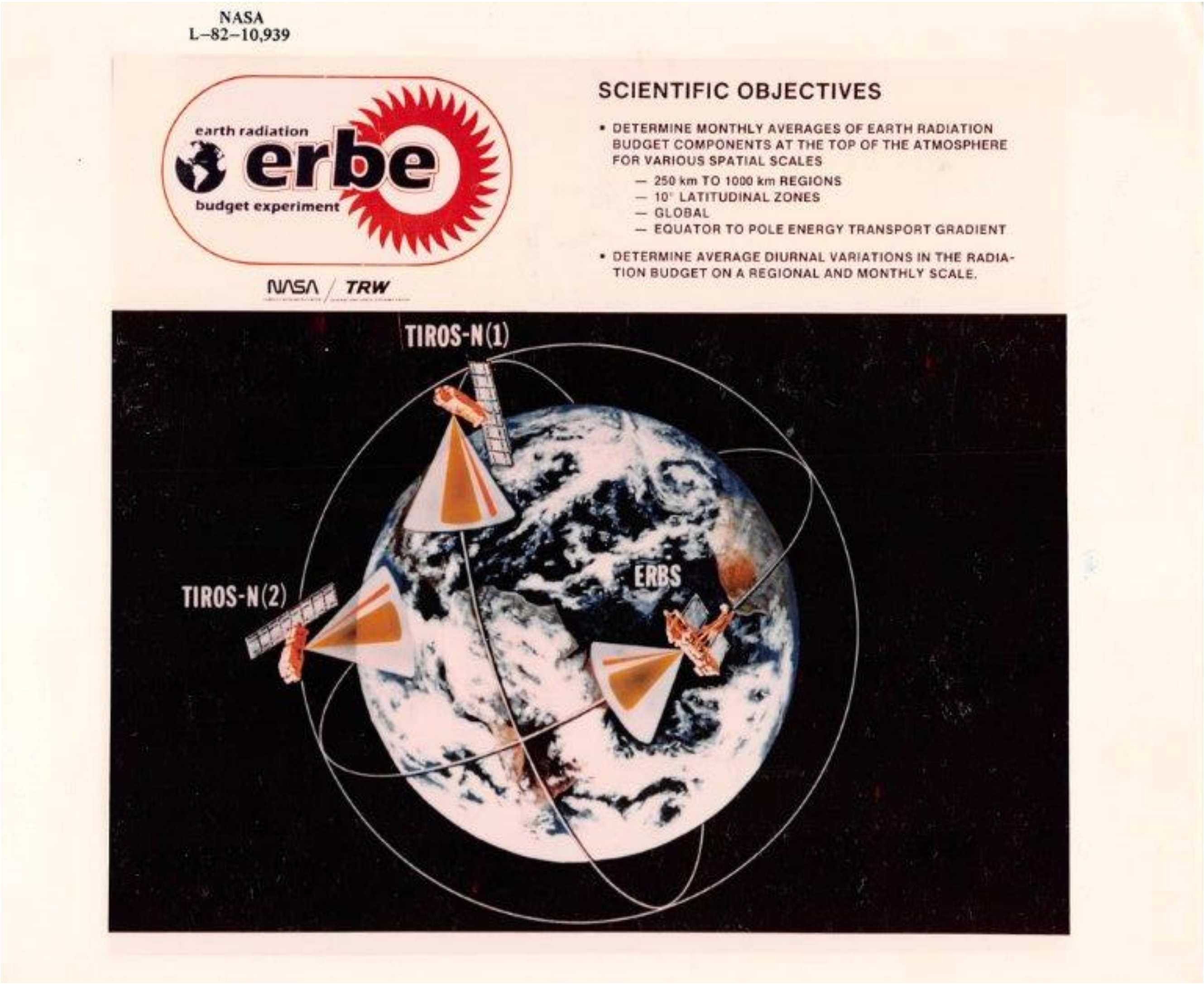
1. Simple instruments with good relative calibration, precision and stability can provide new discoveries.
2. Small satellites can carry very useful instruments…….and there are many opportunities today.

Earth Radiation Budget Satellite (1984-Present)

-for more validation of early results

-for new variability and “cloud forcing” studies

The ERBE 3-satellite constellation plan (note: ERBS was launched into a 57° orbit from Shuttle Challenger Oct. 4, 1984) and the other two instruments were onboard the NOAA-9 and NOAA-10 sunsynchronous weather satellites



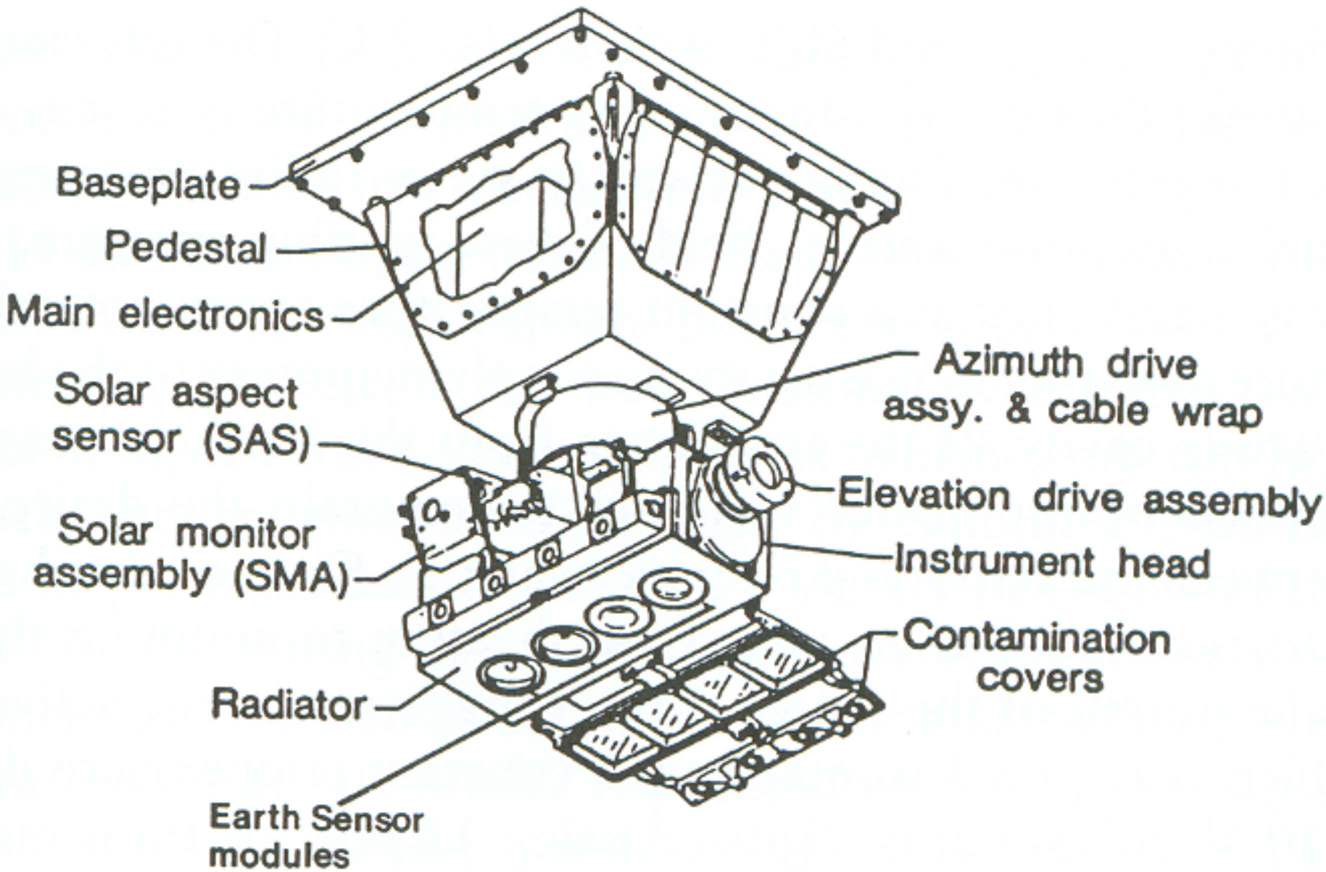


FIGURE 4.15. Diagram of the ERBE Non-Scanner. [After Luther *et al.* (1986).]

Colorado State University CIRA

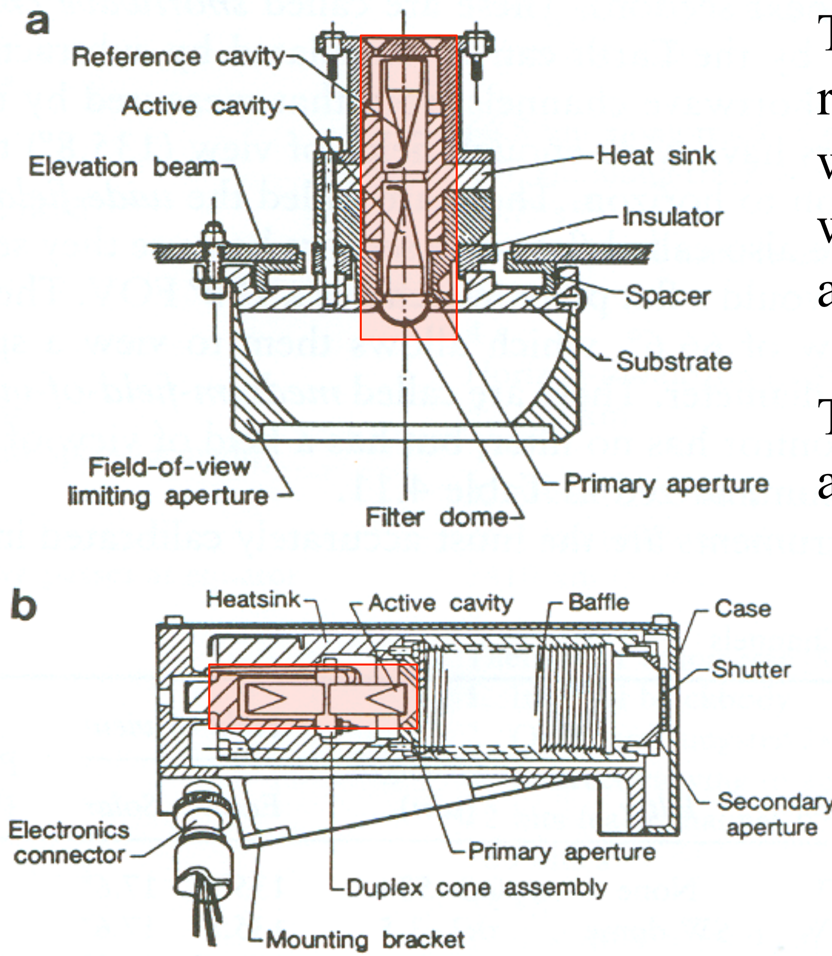
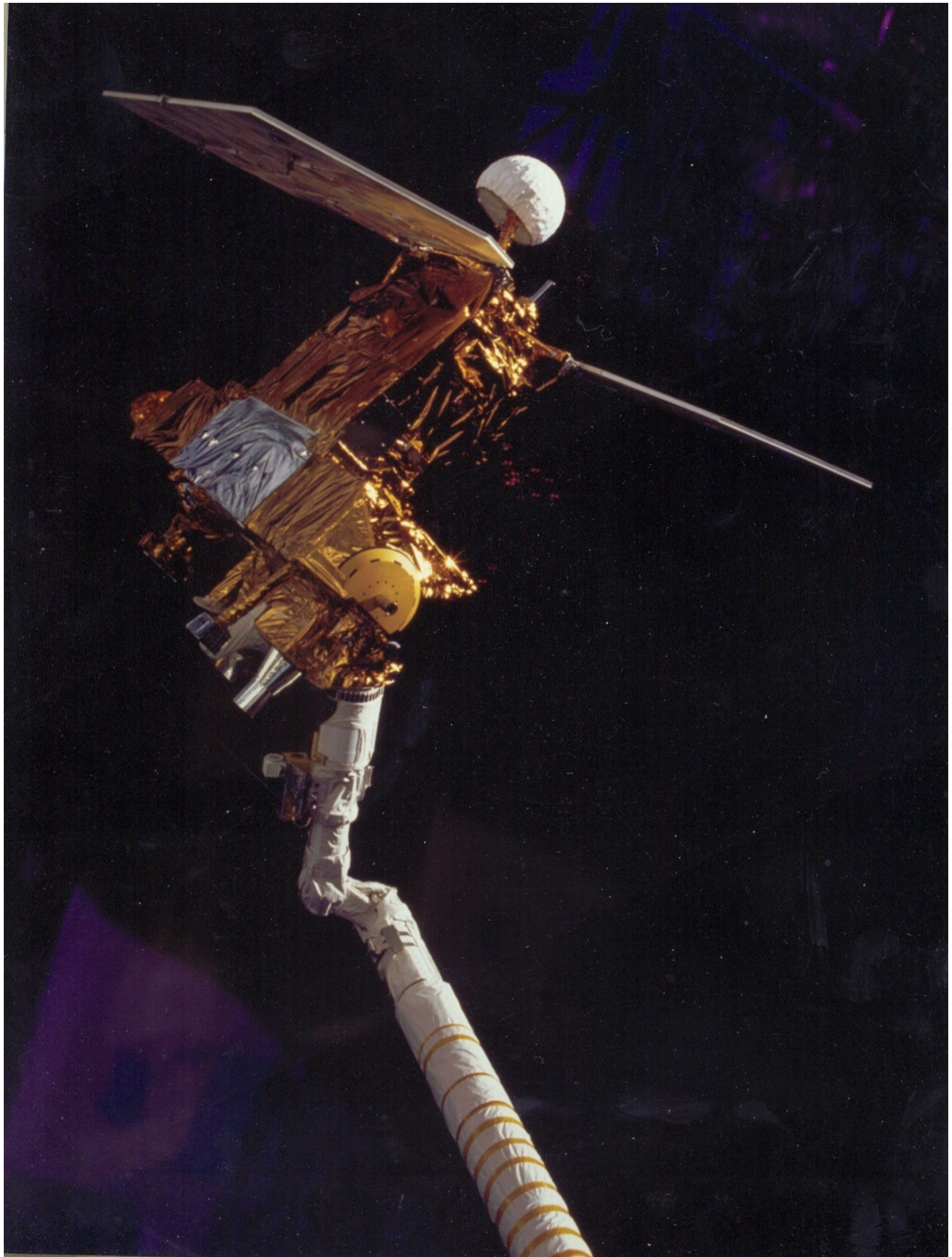


FIGURE 4.16. ERBE-NS active cavity radiometers: (a) Earth sensor module; (b) solar monitor. [After Luther *et al.* (1986).]

These active cavity radiometers for ERBE were designed at CSU with Ball Aerospace and built by TRW –

They lasted > 20 years after launch in 1984.



A 3rd Mission, ERBE, to decrease uncertainty began with the launch of the Earth Radiation Budget Satellite from the Shuttle Challenger on Oct. 4, 1984.

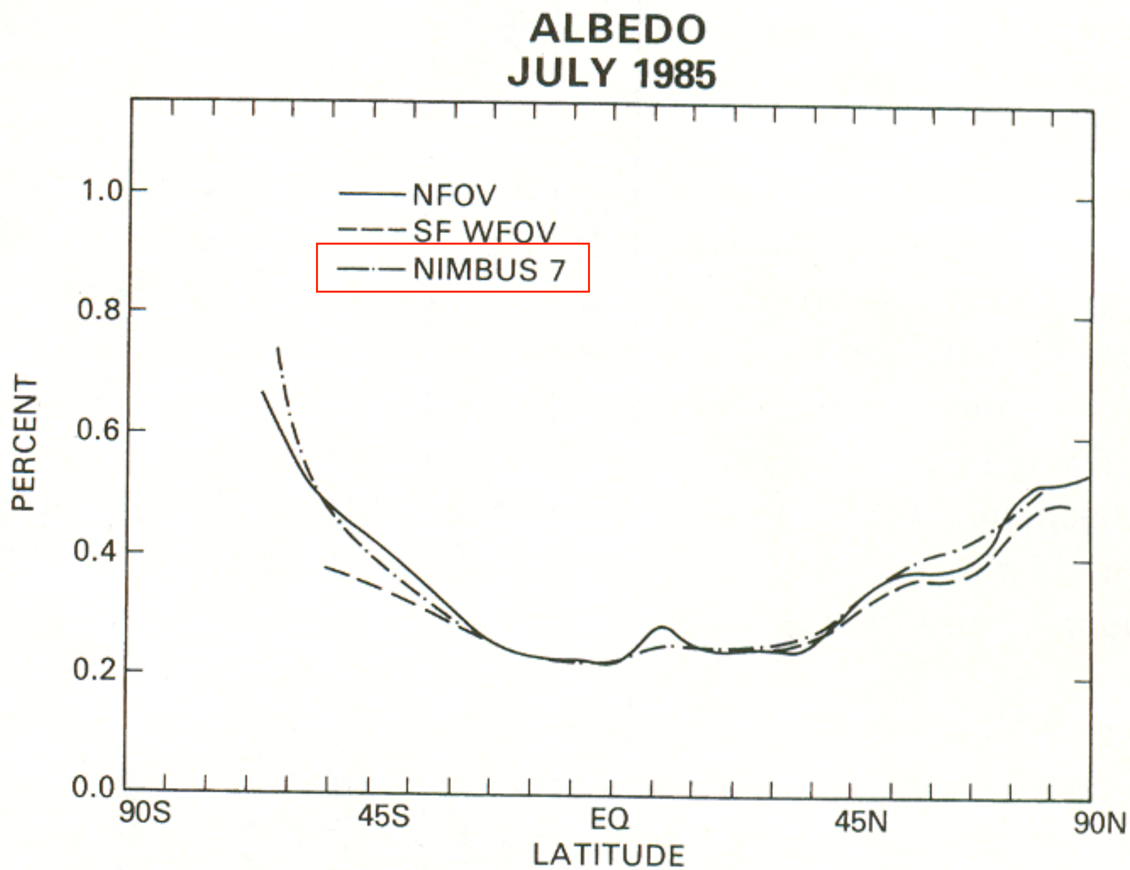


Fig. 8. Comparison of ERBS/NOAA 9 NFOV, WFOV shape factor, and N7 ERB WFOV shape factor albedo latitude band averages for July 1985.

ERBE fits Nimbus and thus <u>the early ERB results from the 1960's have been confirmed</u> and greatly expanded during the 1970's and 1980's

TABLE 5. Time and Space Global Averages and Percent Difference From ERBS/N9 Scanner, 4-Month Average

		F_{LW}, W/m^2	A, %	NR, W/m^2
Scanner				
ERBS/NOAA 9		234.50	29.89	4.79
NOAA 9 only		234.24 (−0.10%)	29.72 (−0.57)	5.63
WFOV				
ERBS/NOAA 9	NF	235.25 (+0.32%)	28.25 (−5.49%)	9.67
	SF	234.11 (−0.17%)	28.83 (−3.55%)	8.89
NOAA 9 only	NF	237.1 (+1.11%)	28.13 (−5.89%)	8.28
	SF	235.43 (+0.40%)	28.75 (−3.81%)	7.72
Nimbus 7 WFOV	SF	234.88 (+0.16)	29.88 (−0.03)	5.62

Units are watts per square meter.

Comparison of Nimbus-7 and the new ERBE results in 1985

(after Kyle et al, 1990)

Having measured – and twice replicated – the fundamental global Earth Radiation Budget provides an important point of confidence for understanding Earth's Climate System.

New knowledge of ERB at TOA helped understand estimates of other components of Earth's energy balance.

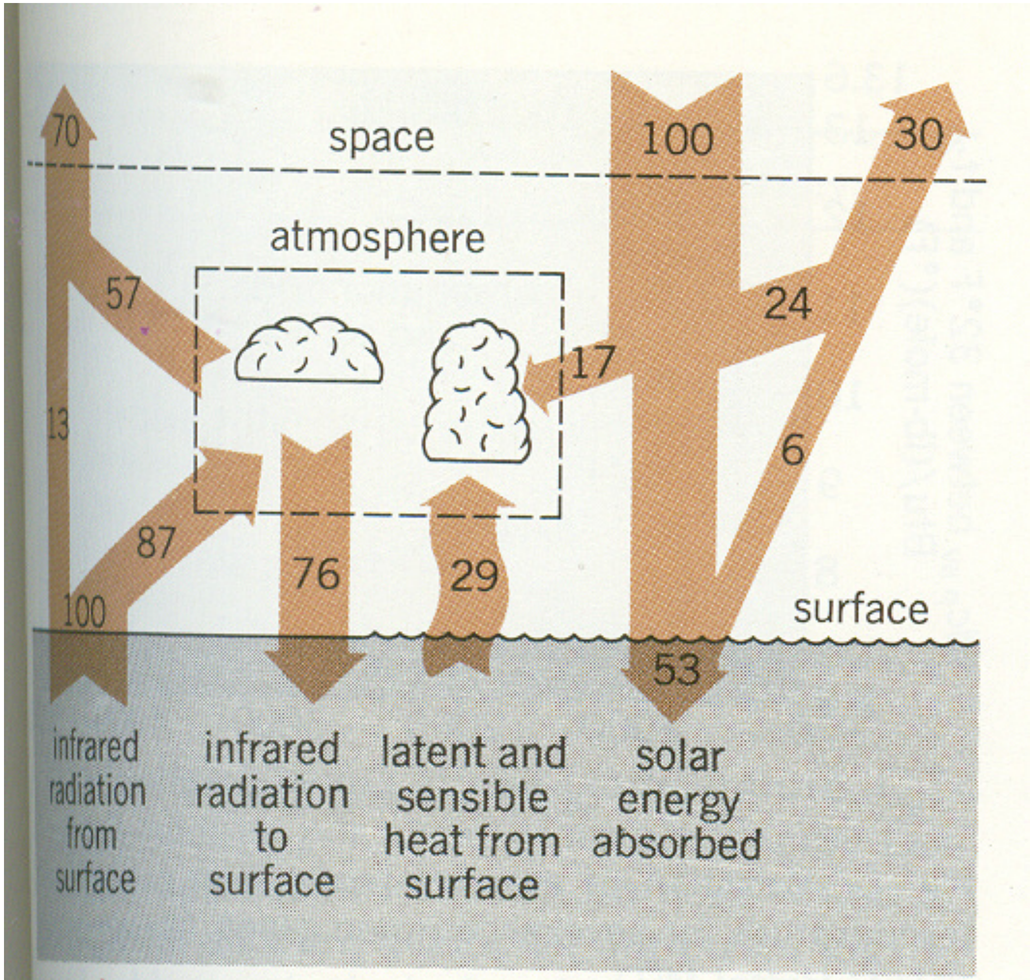


Fig. 1. Average global distribution of incident solar energy and Earth infrared energy throughout the heat balance.

Vonder Haar, T.H., 1987:
"Terrestrial Atmospheric Heat Balance",
McGraw-Hill
Encyclopedia of Science and Technology.
McGraw-Hill Book Company, 6, 413-414.

VOL. 83, NO. C4 JOURNAL OF GEOPHYSICAL RESEARCH APRIL 20, 1978

The Annual Variation in the Global Heat Balance of the Earth

J. S. ELLIS[1] AND T. H. VONDER HAAR

Colorado State University, Fort Collins, Colorado 80523

S. LEVITUS AND A. H. OORT

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, New Jersey 08540

An annual variation with a range of 31 W m^{-2} is found in the global net radiation balance of the earth. The net radiation flux values measured from satellites and the changes in total heat content computed from independent sets of atmospheric and oceanic data show annual variations which are consistent with each other in both phase and magnitude. The net energy gain and loss by the planet within a year is stored and released within the system primarily by the oceans.

± 7 W/m^2 of the annual net radiation cycle is due to Earth-Sun distance, but 3-11 W/m^2 are due to clouds, ice, snow etc.

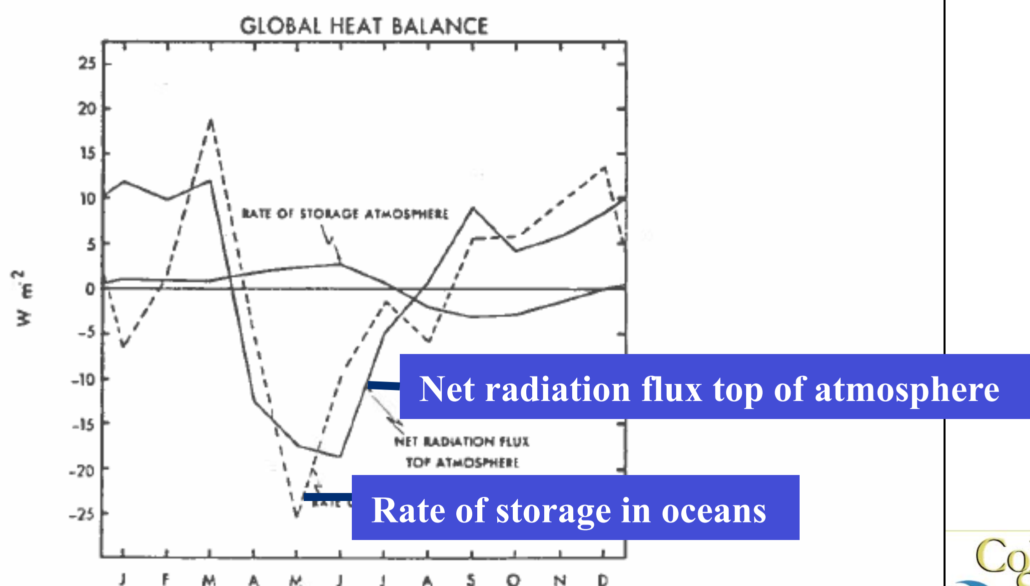


Fig. 4. Principal components of the global heat balance of the earth (in watts per square meter).

SUMMARY OF FIRST RESULTS

- 3 satellite experiments or missions obtained nearly the same global and zonal average Earth Radiation Budget values
- 40% more poleward energy transport is required than thought in the pre-satellite era
- Having measured the mean annual global ERB then research can move on to other components of Earth’s Energy Budget and their space / time variations

LESSONS LEARNED (2 of 2)

3. Remember the scientific method requires reproducibility of results.

4. We are a very multidisciplinary science. Our new results may be of interest in related fields. Engage their interest and comments by publishing in "their" journals.

5. Older data sets of observations should be reanalyzed for new science and applications using today's computers and methods.

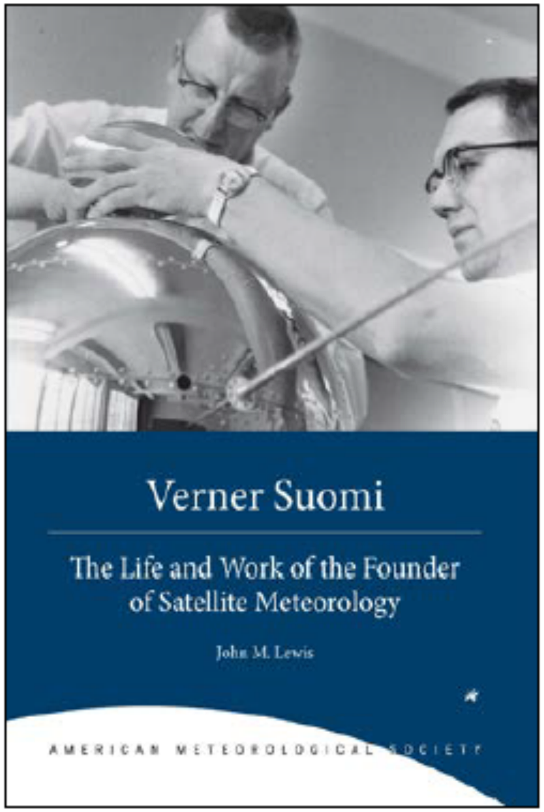
Colorado State University CIRA

For newest Earth Radiation Budget results and more references see:

Stephens, G.L. et al., 2015 : The albedo of Earth, Rev. Geophys., 53, 141-163, doi: 10.1002/2014RG000449.

L'Ecuyer T. S. et al., 2015: The observed state of the energy budget in the early twenty-first century. *J. Clim.,* **28***,* 8319-8346. doi:10.1175/JCLI-D-14-00556.1

Loeb, N. G. et al., 2015 : Observational constraints on atmospheric and oceanic cross-equatorial heat transports: revisiting the precipitation asymmetry problem in climate models, Clim. Dyn., doi 10.1007/s00382-015-2766-z



Verner Suomi

The Life and Work of the Founder of Satellite Meteorology

By John M. Lewis with Jean M. Phillips, W. Paul Menzel, Thomas H. Vonder Haar, Hans Moosmüller, Frederick B. House, and Matthew G. Fearon

ISBN: 9781944970222
List price: \$30 AMS Member price: \$20

As the space age got under way in the wake of *Sputnik*, one of the earliest areas of science to take advantage of the new observational opportunities was the study of climate and weather. This book tells the story of Finnish-American educator, inventor, and scientist Verner Suomi, whose early work in a depression-era Civilian Conservation